

E_6 Unification and the Hidden Sector of the Universe

C.R. Das

Centre for Theoretical Particle Physics, Technical University of Lisbon,
Avenida Rovisco Pais, 1 1049-001 Lisbon, Portugal

L.V. Laperashvili

The Institute of Theoretical and Experimental Physics,
Bolshaya Cheremushkinskaya, 25, 117218 Moscow, Russia

H.B. Nielsen

Theoretical Particle Physics and Cosmology
Niels Bohr Institute, Blegdamsvej 17, 2100 Copenhagen, Denmark

A. Tureanu

Department of Physics, University of Helsinki
and Helsinki Institute of Physics, P.O.Box 64, FIN-00014 Helsinki, Finland

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- 2 Superstring theory and E_6 Unification
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The present paper is devoted to the new Cosmological Model with E_6 unification at the early stage of the Universe, explaining why cosmological constant is extremely small.


The ideas of this talk were published in the following references:


- ① C.R. Das, L.V. Laperashvili, H.B. Nielsen, A. Tureanu,
Mirror World and Superstring-Inspired Hidden Sector of the Universe, Dark Matter and Dark Energy;
arXiv:1101.4558 [hep-ph], to appear in Phys.Rev.D. (2011).
- ② C.R. Das, L.V. Laperashvili, H.B. Nielsen, A. Tureanu,
Baryogenesis in Cosmological Model with Superstring-Inspired E_6 Unification;
Phys.Lett.B **696** (2011), 138; arXiv:1010.2744 [hep-ph].
- ③ C.R. Das, L.V. Laperashvili, A. Tureanu,
Eur.Phys.J.C **66** (2010), 307; arXiv:0902.4874 [hep-ph].


They also were presented at the following conferences:

- ① C.R. Das, L.V. Laperashvili, A. Tureanu,
INVISIBLE UNIVERSE INTERNATIONAL CONFERENCE: *Toward a new cosmological paradigm*, Paris, France, 29 Jun - 3 Jul 2009.
AIP Conf.Proc. **1241** (2010), 639; arXiv:0910.1669 [hep-ph].
- ② C.R. Das, L.V. Laperashvili, A. Tureanu, **Superstring-Inspired E_6 Unification, Shadow Theta-Particles and Cosmology**
A talk given by Larisa Laperashvili at the International Bogolyubov Conference, Moscow-Dubna, August, 2009,
Phys.Part.Nucl. **41** (2010), 965; arXiv:1012.0624 [hep-ph].
- ③ C.R. Das and L.V. Laperashvili, **E_6 unification and Cosmology**, in:
Proceedings of the XIII Int.Conference “Selected Problems of Modern Physics”, dedicated to D.I. Blokhintsev, Dubna, August 2008.

These papers are based on the previously published ideas:

 [P. Q. Hung](#), Nucl. Phys. B **747** (2006), 55;
J. Phys. A **40** (2007), 6871, arXiv:0707.2791.

 [C. R. Das and L. V. Laperashvili](#),
Int. J. Mod. Phys. A **23** (2008), 1863, arXiv:0712.1326 [hep-ph].

 [C. R. Das and L. V. Laperashvili](#),
Phys. Atom. Nucl. **72** (2009), 377 [Yad. Fiz. **72** (2009), 407].







(from now: Refs [Hung et al.](#) and [Das-Laperashvili](#))

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Introduction

Modern models for Dark Energy (DE) and Dark Matter (DM) are based on precise measurements in cosmological and astrophysical observations:

-  [A.G. Riess et al.,](#)
Astron.J. **116**, 1009 (1998); ArXiv: astro-ph/9805201.
-  [S.J. Perlmutter et al.,](#)
Nature **39**, 51 (1998); Astrophys.J. **517**, 565 (1999).
-  [C. Bennett et al.,](#) ArXiv: astro-ph/0302207.
-  [D. Spergel et al.,](#) ArXiv: astro-ph/0302209.
-  [P. Astier et al.,](#) ArXiv: astro-ph/0510447.
-  [D. Spergel et al.,](#) ArXiv: astro-ph/0603449.

See also:



[A.G. Riess et al.,](#)

Astrophys. J. Suppl. **183** (2009), 109; arXiv: 0905.0697.



[W.L. Freedman et al.,](#)

Astrophys. J. **704** (2009), 1036; arXiv: 0907.4524.



[R. Kessler et al.,](#)

arXiv: 0908.4274.

Introduction

Supernovae observations by the Supernovae Legacy Survey (SNLS), cosmic microwave background (CMB), cluster data and baryon acoustic oscillations by the Sloan Digital Sky Survey (SDSS) fit the equation of state for DE:

$$w = p/\rho$$

with constant w and give the following result:

$$w = -1.023 \pm 0.090 \pm 0.054.$$




 [P. Astier et al.](#), ArXiv: astro-ph/0510447.

Introduction

The cosmological constant (CC), the vacuum energy density of the Universe, also is given by the recent astrophysical measurements:

$$CC = \rho_{vac} \approx (2.3 \times 10^{-3} \text{ eV})^4.$$

The value $w = -1$ and a tiny cosmological constant are consistent with the present quintessence model of accelerating expansion of the Universe (so-called Λ CDM scenario):

-  P.J.E. Peebles and A. Vilenkin, Phys.Rev. D **59**, 063505 (1999).
-  C. Wetterich, Nucl.Phys. B **302**, 668 (1998).
-  L.J. Hall, Y. Nomura and S.J. Oliver,
Phys.Rev.Lett. **95**, 141302 (2005); ArXiv: astro-ph/0503706.

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Superstring theory and E_6 Unification

Our model is based on the following assumptions:

- Grand Unified Theory is inspired by the Superstring theory.

The **heterotic** superstring theory $E_8 \times E'_8$ was suggested as a more realistic model for the unification of all fundamental gauge interactions with gravity:



D. J. Gross, J. A. Harvey, E. Martinec and R. Rohm,
Phys. Rev. Lett. **54** (1985), 502; Nucl. Phys. B **256** (1985), 253;
ibid., B **267** (1986), 75.



P. Candelas, G. T. Horowitz, A. Strominger and E. Witten,
Nucl. Phys. B **258** (1985), 46.

Superstring theory and E_6 Unification

This ten-dimensional Yang-Mills theory can undergo the spontaneous breakdown of compactification. The integration over six compactified dimensions of the E_8 superstring theory leads to the effective theory with the E_6 unification in the four-dimensional space:

 M. B. Green, J. H. Schwarz and E. Witten,

Superstring theory

(Cambridge University Press, Cambridge, 1988).

- Superstring theory predicts E_6 unification occurring at the high energy scale $M_{E_6} \approx 10^{18}$ GeV

Three 27-plets of E_6 contain three families of quarks and leptons, including right-handed neutrinos.

We omit generation subscripts, for simplification.

Matter fields (quarks, leptons and scalar fields) of 27-plet decompose under $SU(5) \times U(1)_X$ subgroup as follows:



P. Athron, S.F. King, D. J. Miller, S. Moretti and R. Nevzorov,
Phys. Rev. D **80** (2009) 035009; arXiv:0904.2169; arXiv:0901.1192.

$$27 \rightarrow (10, 1) + (\bar{5}, 2) + (5, -2) + (\bar{5}, -3) + (1, 5) + (1, 0).$$

These representations decompose under the groups with the breaking

$$SU(5) \times U(1)_X \rightarrow SU(3)_C \times SU(2)_L \times U(1)_Z \times U(1)_X.$$

We consider the following $U(1)_Z \times U(1)_X$ charges of matter fields:

$$Z = \sqrt{\frac{5}{3}} Q^Z, \quad X = \sqrt{40} Q^X.$$

We have the following assignments of particles:

$$\begin{aligned}(10, 1) \rightarrow Q &= \begin{pmatrix} u \\ d \end{pmatrix} \sim \left(3, 2, \frac{1}{6}, 1 \right), \\ u^c &\sim \left(\bar{3}, 1, -\frac{2}{3}, 1 \right), \\ e^c &\sim (1, 1, 1, 1). \\ (\bar{5}, 2) \rightarrow d^c &\sim \left(\bar{3}, 1, \frac{1}{3}, 2 \right), \\ L &= \begin{pmatrix} e \\ \nu \end{pmatrix} \sim \left(1, 2, -\frac{1}{2}, 2 \right), \\ (1, 5) \rightarrow S &\sim (1, 1, 0, 5).\end{aligned}$$

$$(5, -2) \rightarrow D \sim \left(3, 1, -\frac{1}{3}, -2 \right),$$

$$h = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix} \sim \left(1, 2, \frac{1}{2}, -2 \right).$$

$$(\bar{5}, -3) \rightarrow D^c \sim \left(\bar{3}, 1, \frac{1}{3}, -3 \right),$$

$$h^c = \begin{pmatrix} h^0 \\ h^- \end{pmatrix} \sim \left(1, 2, -\frac{1}{2}, -3 \right).$$

Also

$$(1, 5) \rightarrow S \sim (1, 5, 0, 0),$$

the SM-singlet field S , which carries nonzero $U(1)_X$ charge.

The light Higgs doublets are accompanied by the heavy colour triplets of exotic quarks (or 'diquarks') D, D^c which are absent in the SM.

The right-handed heavy neutrino is a singlet field of E_6 :

$$(1, 0) \rightarrow N^c \sim (1, 1, 0, 0).$$

It is quite important for baryogenesis.

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The breaking E_6 in the O- and Sh-worlds

It is well known (see, for example:



R. Slansky,

Group Theory for Unified Model Building, Phys.Rept. **79** 1 (1981)

As we have seen, there are three ways of breaking the E_6 group:

- (i) $E_6 \rightarrow SU(3)_1 \times SU(3)_2 \times SU(3)_3$,
- (ii) $E_6 \rightarrow SO(10) \times U(1)$,
- (iii) $E_6 \rightarrow SU(6) \times SU(2)$.

The breaking E_6 in the O- and Sh-worlds

Previously we have considered the model with breaking

$$(1) \ E_6 \rightarrow SU(3)_C \times SU(3)_L \times SU(3)_R.$$

Of course, such a Universe could exist, but then it is difficult to explain a tiny value of CC .

In the present investigation we adopt for the O-world the breaking $E_6 \rightarrow SO(10) \times U(1)$,

while for the Sh-world we consider the breaking $E'_6 \rightarrow SU(6)' \times SU(2)'$.

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Mirror and Shadow worlds

Superstring theory has led to the speculation that there may exist in the Universe another form of matter - “**shadow matter**”:



E. W. Kolb, D. Seckel and M. S. Turner,
Nature **314** (1985), 415; Fermilab-Pub-85/16-A, Jan.1985.

This shadow matter interacts with ordinary matter only via gravity, or gravitational-strength interactions.


Shadow world is an extension of the concept of the Mirror World (MW) — a mirror duplication of our Ordinary World (OW).

Mirror and Shadow worlds

Lee and Yang were the first to suggest such a duplication of the worlds, which restores the left-right symmetry of Nature:

 [T.D. Lee and C.N. Yang](#), Phys. Rev. **104** (1956), 254.

They introduced a concept of right-handed particles, but their R-world was not hidden.

 [I.Yu. Kobzarev, L.B. Okun and I.Ya. Pomeranchuk](#),
Yad. Fiz. **3** (1966), 1154 [Sov. J. Nucl. Phys. **3** (1966), 837]
introduced the term 'Mirror Matter' and 'Mirror World' (MW) as the hidden sector of our Universe. They demonstrated that a mirror copy of the ordinary world interacts with our visible O-world only via gravity or other very weak interactions.

Mirror and Shadow worlds

The next assumptions:

- We assume that there exists a **Shadow World (Sh-world)** (hidden sector), parallel to our ordinary (visible) world, but it is not identical with our O-world, having different symmetry groups.
- Shadow world describes the Dark Energy (DE) and Dark Matter (DM) existing in our Universe:
see References **Hung et al. and Das-Laperashvili.**
- We assume that E_6 unification had a place in the Ordinary and Mirror worlds at the early stage of our Universe. This means that at high energy scale $\approx 10^{18}$ GeV the Mirror World exists and the group of symmetry of the Universe is $E_6 \times E'_6$ (the superscript 'prime' denotes the M- or Sh-world).

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The particle content in the ordinary and mirror worlds

If we have in Nature ordinary and mirror worlds then at low energies we can describe them by a minimal symmetry

$$G_{SM} \times G'_{SM},$$

where

$$G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$$

stands for the Standard Model (SM) of observable particles: three generations of quarks and leptons and the Higgs boson.

Then

$$G'_{SM} = SU(3)'_C \times SU(2)'_L \times U(1)'_Y$$

is its mirror gauge counterpart having three generations of mirror quarks and leptons and the mirror Higgs boson.

The M-particles are singlets of G_{SM} and the O-particles are singlets of G'_{SM} .

The particle content in the ordinary and mirror worlds

Including the Higgs bosons Φ , we have the following SM content of the O-world:

L – set : $(u, d, e, \nu, \tilde{u}, \tilde{d}, \tilde{e}, \tilde{N})_L, \Phi_u, \Phi_d;$

\tilde{R} – set : $(\tilde{u}, \tilde{d}, \tilde{e}, \tilde{\nu}, u, d, e, N)_R, \tilde{\Phi}_u, \tilde{\Phi}_d;$

with the antiparticle fields: $\tilde{\Phi}_{u,d} = \Phi_{u,d}^*, \tilde{\psi}_R = C\gamma_0\psi_L^*$ and $\tilde{\psi}_L = C\gamma_0\psi_R^*$.

Considering the minimal symmetry $G_{SM} \times G'_{SM}$, we have the following particle content in the M-sector:

L' – set : $(u', d', e', \nu', \tilde{u}', \tilde{d}', \tilde{e}', \tilde{N}')_L, \Phi'_u, \Phi'_d;$

\tilde{R}' – set : $(\tilde{u}', \tilde{d}', \tilde{e}', \tilde{\nu}', u', d', e', N')_R, \tilde{\Phi}'_u, \tilde{\Phi}'_d.$

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Mirror world with broken mirror parity

If the ordinary and mirror worlds are identical, then O- and M-particles should have the same cosmological densities. But this is in the immediate conflict with recent astrophysical measurements.

Mirror parity (MP) is not conserved, and the ordinary and mirror worlds are not identical:

 [Z. Berezhiani, A. Dolgov and R. N. Mohapatra,](#)
Phys. Lett. B **375** (1996), 26, hep-ph/9511221.





 [Z. Berezhiani and R. N. Mohapatra,](#)
Phys. Rev. D **52** (1995), 6607, hep-ph/9505385.

 [Z. Berezhiani,](#) *Through the looking-glass: Alice's adventures in mirror world*, in: Ian Kogan Memorial Collection "From Fields to Strings: Circumnavigating Theoretical Physics", Ed. M. Shifman et. al., World Scientific, Singapore, Vol. 3, pp. 2147-2195, 2005, hep-ph/0508233.

From here [Berezhiani-Dolgov-Mohapatra](#).

Mirror world with broken mirror parity

Similar ideas were considered in references:

-  [R. Foot, H. Lew and R.R. Volkas,](#)
Phys.Lett.B **272** (1991), 67; Mod.Phys.Lett.A **7** (1992), 2567.
-  [R. Foot,](#)
Mod.Phys.Lett.A **9** (1994), 169.
-  [R. Foot and R.R. Volkas,](#)
Phys.Rev.D **55** (1995), 5147.
-  [Review by R. Foot](#)
Int.J.Mod.Phys.D **13** (2004), 2161.

Mirror world with broken mirror parity

In the case of non-conserved MP the VEVs of the Higgs doublets Φ and Φ' are not equal:

$$\langle \Phi \rangle = v, \quad \langle \Phi' \rangle = v', \quad v \neq v'.$$

We introduced the parameter characterizing the violation of MP:

$$\zeta = \frac{v'}{v} \gg 1.$$

Then the masses of fermions and massive bosons in the mirror world are scaled up by the factor ζ with respect to the masses of their counterparts in the ordinary world:

$$m'_{q',l'} = \zeta m_{q,l}, \quad M'_{W',Z',\Phi'} = \zeta M_{W,Z,\Phi},$$

while photons and gluons remain massless in both worlds.

Mirror world with broken mirror parity

The value of ζ was estimated by astrophysical implications in Refs. [Berezhiani-Dolgov-Mohapatra](#): $\zeta \approx 30$.

In the language of neutrino physics:

the O-neutrinos ν_e, ν_μ, ν_τ are **active neutrinos**,

while the M-neutrinos $\nu'_e, \nu'_\mu, \nu'_\tau$ are **sterile neutrinos**.

If MP is conserved ($\zeta = 1$), then neutrinos of two sectors are strongly mixed. But it seems that the situation with the present experimental and cosmological limits on the active-sterile neutrino mixing do not confirm this result.

If instead MP is spontaneously broken, and $\zeta \gg 1$, then the active-sterile mixing angles should be small: $\theta_{\nu\nu'} \sim \frac{1}{\zeta}$. As a result, we have the following relation between the masses of the light left-handed neutrinos:
$$m'_{\nu} \approx \zeta^2 m_{\nu}.$$

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Seesaw scale in the ordinary and mirror worlds

In the context of the SM, theory predicts that so called right-handed neutrinos N_a with large Majorana mass terms have equal masses in the O- and M(Sh)-worlds:

$$M'_{\nu,a} = M_{\nu,a}.$$

Heavy right-handed neutrinos are created at seesaw scale M_R (or M'_R) in the O- (or M(Sh)-)world.

Theory predicts that even in the model with broken mirror parity, we have the same seesaw scales in both worlds:


$$M'_R = M_R.$$

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The breaking E_6 in the O- and Sh- worlds


It is well known (see, for example:

 [R. Slansky](#), *Group Theory for Unified Model Building*,
Phys.Rept. **79** 1 (1981))

As was mentioned, three ways of breaking the E_6 group:

- (i) $E_6 \rightarrow SU(3)_1 \times SU(3)_2 \times SU(3)_3$,
- (ii) $E_6 \rightarrow SO(10) \times U(1)$,
- (iii) $E_6 \rightarrow SU(6) \times SU(2)$.

The first case was considered in our paper:

 [C.R. Das](#), [L.V. Laperashvili](#), [H.B. Nielsen](#) and [A. Tureanu](#),
Mirror World and Superstring-Inspired Hidden Sector of the Universe,
Dark Matter and Dark Energy.
arXiv:1101.4558 [hep-ph], to appear in Phys.Rev.D (2011).

From here Ref. DLNT.

The breaking E_6 in the O- and Sh- worlds

Here we have investigated the possibility of the breaking:

$$E_6 \rightarrow SU(3)_C \times SU(3)_L \times SU(3)_R$$

in both O- and M-worlds, with broken MP.

The model has the merit of an attractive simplicity.

However, in such a model we are unable to explain the tiny CC , given by astrophysical measurements, because in this case we have in both worlds the low-energy limit of the SM, which forbids a large confinement radius (i.e. small energy scale) of any interaction.

It is quite impossible to obtain the same E_6 unification in the O- and M-worlds with the same breakings (ii) or (iii) in both worlds if mirror parity MP is broken.

The breaking E_6 in the O- and Sh- worlds

In this case, we are forced to assume different breakings of the E_6 unification in the O- and Sh-worlds:

$$\begin{aligned} E_6 &\rightarrow SO(10) \times U(1) && \text{in O - world,} \\ E'_6 &\rightarrow SU(6)' \times SU(2)' && \text{in Sh - world,} \end{aligned}$$

This breaking explains the small value of the CC by condensation of fields belonging to the additional $SU(2)'$ gauge group which exists only in the Sh-world and has a large confinement radius.

The breaking E_6 in the O- and Sh- worlds

The breaking mechanism of the E_6 unification is given in Ref:



Taichiro Kugo, Joe Sato,

Prog. Theor. Phys. **91** (1994) 1217; hep-ph/9402357.

The vacuum expectation values (VEVs) of the Higgs fields H_{27} and H_{351} belonging to 27- and 351-plets of the E_6 group can appear in the case (iii) for the O-world only with nonzero 27-component:

$$\langle H_{351} \rangle = 0, \quad v = \langle H_{27} \rangle \neq 0.$$

In the case (iii) for the Sh-world we have

$$\langle H_{27} \rangle = 0, \quad V = \langle H_{351} \rangle \neq 0.$$

The breaking E_6 in the O- and Sh- worlds

The 27 representation of E_6 is decomposed into $1 + 16 + 10$ under the $SO(10)$ subgroup and the 27 Higgs field H_{27} is expressed in 'vector' notation as

$$H_{27} \equiv \begin{pmatrix} H_0 \\ H_\alpha \\ H_M \end{pmatrix},$$

where the subscripts 0, $\alpha = 1, 2, \dots, 16$ and $M = 1, 2, \dots, 10$ stand for singlet, the 16- and the 10-representations of $SO(10)$, respectively. Then

$$\langle H_{27} \rangle = \begin{pmatrix} v \\ 0 \\ 0 \end{pmatrix}.$$

Taking into account that the 351 – *p*let of E_6 is constructed from 27×27 symmetrically, we see that the trace part of H_{351} is a singlet under the maximal little groups. Therefore, in a suitable basis, we can construct the VEV $\langle H_{351} \rangle$ for the case of the maximal little group $SU(2) \times SU(6)$.

The breaking E_6 in the O- and Sh- worlds

A singlet under this group which we get from a symmetric product of 27×27 comes from the component

$$(1, 15) \times (1, 15)$$

and hence

$$\langle H_{351} \rangle = \begin{pmatrix} V \otimes 1_{15} & \\ & 0 \otimes 1_{15} \end{pmatrix}.$$

According to the assumptions of DLNT-paper, in the ordinary world there exists the following chain of symmetry groups from the GUT scale (M_{E6}) of the E_6 unification down to the Standard Model (SM) scale (M_{EW}):

$$\begin{aligned} E_6 &\rightarrow SO(10) \times U(1)_Z \rightarrow SU(4)_C \times SU(2)_L \times SU(2)_R \times U(1)_Z \\ &\rightarrow SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_X \times U(1)_Z \\ &\rightarrow [SU(3)_C \times SU(2)_L \times U(1)_Y]_{SUSY} \rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y. \end{aligned}$$

The breaking E_6 in the O- and Sh- worlds

In the shadow Sh-world, we have the following chain:

$$\begin{aligned} E'_6 &\rightarrow SU(6)' \times SU(2)'_\theta \rightarrow SU(4)'_C \times SU(2)'_L \times SU(2)'_\theta \times U(1)'_Z \\ &\rightarrow SU(3)'_C \times SU(2)'_L \times SU(2)'_\theta \times U(1)'_X \times U(1)'_Z \\ &\rightarrow [SU(3)'_C \times SU(2)'_L \times SU(2)'_\theta \times U(1)'_Y]_{SUSY} \\ &\rightarrow SU(3)'_C \times SU(2)'_L \times SU(2)'_\theta \times U(1)'_Y. \end{aligned}$$

In general, this is not an unambiguous choice of the $E_6(E'_6)$ breaking chains. The unification $E_6 = E'_6$ restores the mirror parity MP at the scale:

$$M'_{E_6} = M_{E_6} \simeq 10^{18} \text{ GeV}.$$

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New shadow gauge group $SU(2)'_{\theta}$

Now we are confronted with the question:

What group of symmetry $SU(2)'$, unknown in the O-world, exists in the Sh-world, ensuring the E'_6 unification?

We assume that this new $SU(2)'$ group is precisely the $SU(2)'_{\theta}$ gauge group of symmetry suggested by **L.B. Okun**.

L. B. Okun, JETP Lett. **31** (1980) 144; Pisma Zh. Eksp. Teor. Fiz. **31** (1979) 156; Nucl. Phys. B **173** (1980) 1.

The reason for our choice of the $SU(2)'_{\theta}$ group was to obtain the evolution $\alpha'^{-1}_{2\theta}(\mu)$, which leads to the new scale in the shadow world at extremely low energies.

New shadow gauge group $SU(2)'_{\theta}$

In the works by L.B.Okun it was suggested the hypothesis that in Nature there exists the symmetry group

$$G_{\theta} = SU(3)_C \times SU(2)_L \times SU(2)_{\theta} \times U(1)_Y ,$$

i.e. with an additional non-Abelian $SU(2)_{\theta}$ group whose gauge fields are neutral, massless vector particles – ‘thetons’.

These ‘thetons’ have a macroscopic confinement radius $1/\Lambda_{\theta}$.

New shadow gauge group $SU(2)'_{\theta}$

Later, in Refs.:



P.Q. Hung,

Nucl. Phys. B **747** (2006) 55; J. Phys. A **40** (2007) 6871;



P.Q. Hung and P. Mosconi, hep-ph/0611001;



M. Adibzadeh and P. Q. Hung, Nucl. Phys. B **804** (2008) 223;



H. Goldberg, Phys. Lett. B **492** (2000) 153;



C. R. Das and L.V. Laperashvili,

Int. J. Mod. Phys. A **23** (2008) 1863; arXiv:0712.1326 [hep-ph; Phys. Atom. Nucl. **72** (2009) 377; arXiv:0712.0253 [hep-ph].

it was assumed that if there exists any $SU(2)$ group with the scale

$$\Lambda_2 \sim 10^{-3} \text{eV},$$

then it is possible to explain the small value of the observable CC .

New shadow gauge group $SU(2)'_\theta$

This idea was taken up in Refs.:

 C.R. Das, L.V. Laperashvili and A. Tureanu,

Eur.Phys.J.C **66** (2010) 307; arXiv:0902.4874; AIP Conf.Proc. **1241** (2010) 639; arXiv:0910.1669.

Since this moment and further: Ref. DLT. Here we assume the existence of low-energy symmetry group G_θ) only in the Sh-world: theta-particles are absent in the O-world, because their existence is in disagreement with all experiments. However, they can exist in the Sh-world:

$$G' = SU(3)'_C \times SU(2)'_L \times SU(2)'_\theta \times U(1)'_Y,$$

Now we consider shadow thettons $\Theta'^i_{\mu\nu}$, $i = 1, 2, 3$, which belong to the adjoint representation of the group $SU(2)'_\theta$, three generations of shadow theta-quarks q'_θ and shadow theta-leptons l'_θ , and the necessary theta-scalars ϕ'_θ for the corresponding breakings.

New shadow gauge group $SU(2)'_{\theta}$

Shadow thetons have macroscopic confinement radius $1/\Lambda'_{\theta}$, and we assume that

$$\Lambda'_{\theta} \sim 10^{-3} \text{ eV}.$$

Matter fields of the fundamental 27-representation of the E'_6 group decompose under $SU(2)'_{\theta} \times SU(6)'$ subgroup as follows:

$$27 = (2, 6) + (1, 15),$$

New shadow gauge group $SU(2)'_{\theta}$

Where

$$\begin{aligned}(2, 6) &\rightarrow q' = \begin{pmatrix} q'_{\theta, A} |_{I_{\theta}=+1/2} \\ q'_{\theta, A} |_{I_{\theta}=-1/2} \end{pmatrix}. \\ (1, 15) &\rightarrow D', D'^c \\ &h' = \begin{pmatrix} h'^+ \\ h'^0 \end{pmatrix}, \\ &h'^c = \begin{pmatrix} h'^0 \\ h'^- \end{pmatrix}, \\ &q'^c_a, N'^c, S'.\end{aligned}$$

Here $A = 1, \dots, 6$; $a = 1, 2, 3$ are color indices and I_{θ} is a theta-isospin; theta-quarks are $q'_{\theta, A}$, while quarks q'^c_a , right-handed neutrino N'^c and scalar S' are $SU(2)'_{\theta}$ -singlets.

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The running of the inverse coupling constants

Let us consider now the running of the inverse coupling constants in the SM and SM':

$$\alpha_i^{-1}(\mu) = \frac{b_i}{2\pi} \ln \frac{\mu}{\Lambda_i}, \quad \text{in the O-world,}$$
$$\alpha_i'^{-1}(\mu) = \frac{b_i'}{2\pi} \ln \frac{\mu}{\Lambda_i'}, \quad \text{in the M-world,}$$

where μ is the energy scale.

And $\alpha_i^{(\prime)} = \frac{g_i^{(\prime)2}}{4\pi}$, $g_i^{(\prime)}$ is the gauge coupling constant of the gauge group $G_i^{(\prime)}$.

Here $i = 1, 2, 3$ correspond to $U(1)$, $SU(2)$ and $SU(3)$ groups of the SM (or SM').

Notations: here and below the ordinary world is given by the non-primed symbols, while mirror or shadow world is given by the primed symbols.

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The running of coupling constants

In this section we consider the running of all the inverse gauge coupling constants in the O- and Sh-worlds.

They are well described by the one-loop approximation of the renormalization group equations (RGEs), since from the Electroweak (EW) scale up to the Planck scale (M_{Pl}) all the non-Abelian gauge theories with rank $r \geq 2$ appearing in our model are chosen to be **asymptotically free**.

Considering Sh-world we have used the values of parameters ζ and ξ estimated by [Berezhiani-Dolgov-Mohapatra](#) from astrophysical measurements:

$$\zeta = 30 \quad \text{and} \quad \xi = 1.5, \quad \xi = \frac{\Lambda'_i}{\Lambda_i}$$

The running of coupling constants

We start with the SM in the ordinary world:

$$G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$$

and with $SM' \times SU(2)'_\theta$ in the shadow world:

$$G'_\theta = SU(3)'_C \times SU(2)'_L \times SU(2)'_\theta \times U(1)'_Y.$$

Now we must consider the content of particles for the $SU(2)'_\theta$ gauge group. By analogy with the theory developed by L.B. Okun, we have shadow thetens $\Theta'^i_{\mu\nu}$ ($i = 1, 2, 3$), which belong to the adjoint representation of $SU(2)'_\theta$, three generations of shadow theta-quarks q'_θ , shadow leptons l'_θ , and theta-scalars ϕ'_θ as doublets of $SU(2)'_\theta$.

Calculating the slopes for the running $\alpha'^{-1}_{2\theta}$:

$b_{2\theta} = 3$ and $b^{\text{SUSY}}_{2\theta} = -2$, it is easy to obtain the value:

$$\Lambda'_\theta \sim 10^{-3} \text{ eV}.$$

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The Minimal Supersymmetric Standard Model ($MSSM^{(')}$) (which extends the conventional $SM^{(')}$) gives the running of the inverse coupling constants from the supersymmetric scale $M_{SUSY}^{(')}$ up to the seesaw scale $M_R^{(')}$, where the heavy (shadow) right-handed neutrinos are produced.

In $MSSM'$ the superpartners of particles, i.e., **shadow “sparticles”**, have the following heavy masses: $\tilde{m}' = \zeta \tilde{m}$, and the supersymmetry breaking scale in the Sh-world is larger:

$$M'_{SUSY} = \zeta M_{SUSY},$$

but seesaw scale is the same as in the O-world:

$$M'_R = M_R.$$

The running of coupling constants in the O-world

The running of the inverse coupling constants as functions of $x = \log_{10} \mu$, where μ is the energy variable, is presented for O-world in **Fig. 1,2**, using the scales $M_{SUSY} = 10$ TeV and $M_R = 2.5 \cdot 10^{14}$ GeV. In these figures, red lines correspond to the ordinary world.

Here:

$$M_{GUT} = 1.1 \cdot 10^{16} \text{ GeV},$$

$$M'_{GUT} = 6.37 \cdot 10^{17} \text{ GeV},$$

$$M_{E_6} \approx 6.96 \cdot 10^{17} \text{ GeV},$$

$$\alpha_{E_6}^{-1} \approx 27.64.$$

Fig. 2 shows the running of the gauge coupling constants near the scale of the E_6 unification for $x \geq 15$.

The running of coupling constants in the O-world

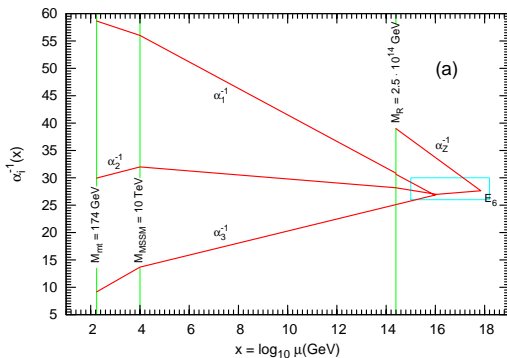


Fig.: This **Fig. 1** presents the running of the inverse coupling constants $\alpha_i^{-1}(x)$ in the ordinary world from the Standard Model up to the E_6 unification for SUSY breaking scale $M_{\text{SUSY}} = 10 \text{ TeV}$ and seesaw scale $M_R = 2.5 \cdot 10^{14} \text{ GeV}$. This case gives: $M_{E_6} \approx 6.96 \cdot 10^{17} \text{ GeV}$ and $\alpha_{E_6}^{-1} \approx 27.64$.

The running of coupling constants in the O-world

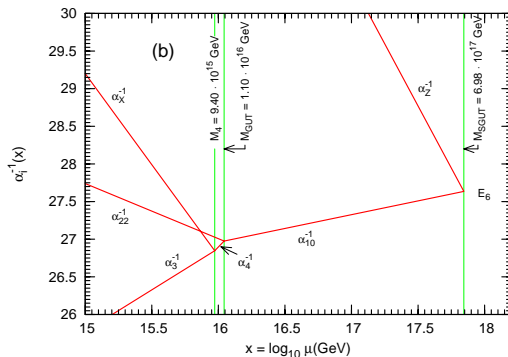


Fig.: This **Fig. 2** is the same as **Fig. 1**, but zoomed in the scale region from 10^{15} GeV up to the E_6 unification to show the details.

The running of the coupling constants in the Sh-world

The running of the inverse coupling constants as functions of $x = \log_{10} \mu$ is presented for Sh-world in Fig. 3,4, using the scales $M'_{SUSY} = \zeta M_{SUSY} = 300 \text{ TeV}$ and $M'_R = M_R = 2.5 \cdot 10^{14} \text{ GeV}$. In these figures, blue lines correspond to the shadow world.

Fig. 4 shows the running of the gauge coupling constants near the scale of the E_6 unification for $x \geq 15$.

Here we see the running of the θ -coupling constant $\alpha'_{2\theta}{}^{-1}$.

The running of the coupling constants in the Sh-world

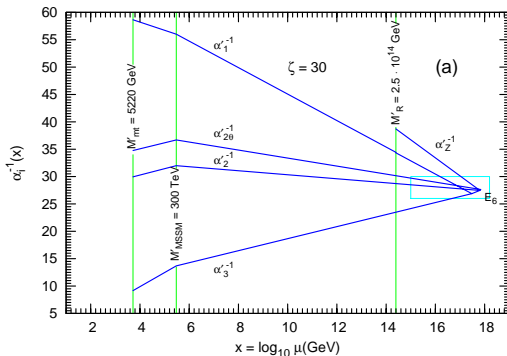


Fig. 3 presents the running of the inverse coupling constants $\alpha_i^{-1}(x)$ in the shadow world from the Standard Model up to the E_6 unification for shadow SUSY breaking scale $M'_{\text{SUSY}} = 300 \text{ TeV}$ and shadow seesaw scale $M'_R = M_R = 2.5 \cdot 10^{14} \text{ GeV}$; $\zeta = 30$. This case gives: $M_{E_6} = 6.96 \cdot 10^{17} \text{ GeV}$ and $\alpha_{E_6}^{-1} = 27.64$.

The running of the coupling constants in the Sh-world

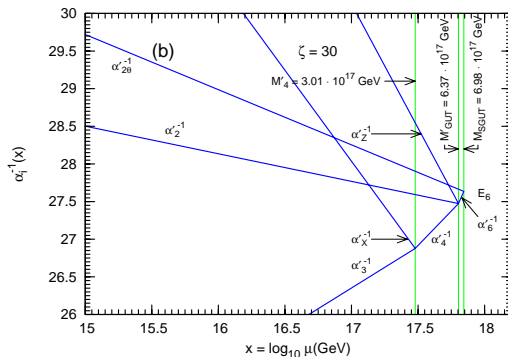


Fig.: This **Fig. 4** is the same as **Fig. 3**, but zoomed in the scale region from 10^{15} GeV up to the E_6 unification to show the details.

The running of the coupling constants in the Sh-world

The comparison of the evolutions in the O- and Sh-worlds is presented in **Figs. 5,6.**

The parameters of our model are as follows: $M_{SUSY} = 10$ TeV, $\zeta = 30$. In this case we have: $M'_{SUSY} = 300$ TeV, $M_R = M'_R = 2.5 \cdot 10^{14}$ GeV, Here $M_{GUT} = 1.10 \cdot 10^{16}$ GeV \rightarrow for $SO(10)$, $M'_{GUT} = 6.37 \cdot 10^{17}$ GeV \rightarrow for $SU'(6)$, $M_{E_6} = 6.96 \cdot 10^{17}$ GeV, and $\alpha_{E_6}^{-1} = 27.64$.

The running of the coupling constants in the Sh-world

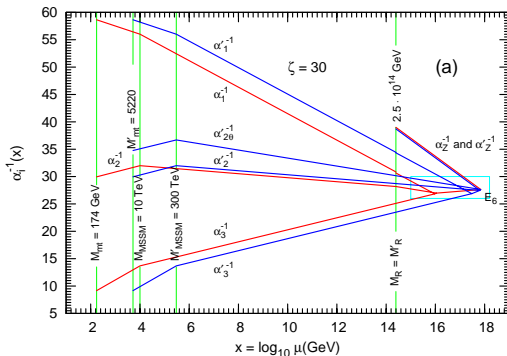


Fig. 5 shows the running of the inverse coupling constants $\alpha_i^{-1}(x)$ in both ordinary and mirror worlds with broken mirror parity, from the Standard Model up to the E_6 unification for SUSY breaking scales $M_{\text{SUSY}} = 10 \text{ TeV}$, $M'_{\text{SUSY}} = 300 \text{ TeV}$ and seesaw scales $M_R = M'_R = 2.5 \cdot 10^{14} \text{ GeV}$, $\zeta = 30$. This case gives: $M_{E_6} = 6.96 \cdot 10^{17} \text{ GeV}$ and $\alpha_{E_6}^{-1} = 27.64$.

The running of the coupling constants in the Sh-world

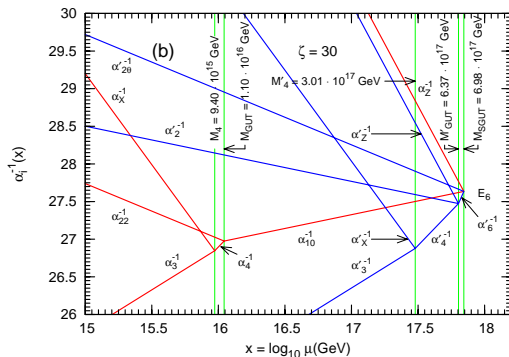


Fig.: This **Fig. 6** is the same as **Fig. 5**, but zoomed in the scale region from 10^{15} GeV up to the E_6 unification to show the details.

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Inflation, E_6 unification and the problem of walls

The simplest model of inflation is based on the superpotential:

$$W = \lambda\varphi(\Phi^2 - \mu^2).$$

It contains the inflaton field given by φ (singlet of E_6) and the Higgs field Φ .

λ is a coupling constant of order 1 and μ is a dimensional parameter of the order of the GUT scale:

See, for example,



G. Dvali, Q. Shafi, R. Schaefer, Phys.Rev.Lett. **73** (1994) 1886.


The supersymmetric vacuum is located at $\varphi = 0$, $\Phi = \mu$.

Inflation, E_6 unification and the problem of walls

But for the field values $\Phi = 0$, $|\varphi| > \mu$ the tree level potential has a flat valley with the energy density $V = \lambda^2 \mu^4$.

When the supersymmetry is broken by the non-vanishing F-term, the flat direction is lifted by radiative corrections and the inflaton potential acquires a slope appropriate for the slow roll conditions.

This so-called hybrid inflation model leads to the choice of the initial conditions:

 Z. Berezhiani, D. Comelli and N. Tetradis,
Phys. Lett. B **431** (1998) 286.

Inflation, E_6 unification and the problem of walls

Namely, at the end of the Planck epoch the singlet scalar field φ should have an initial value

$$\varphi = f \sim 10^{18} \text{ GeV}$$

e.g. $\sim E_6$ -GUT scale, while the field Φ must be zero with high accuracy over a region much larger than the initial horizon size $\sim M_{Pl}$.

In other words, the initial field configuration should be located right on the bottom of the inflaton valley and the energy density starts with

$$V = \lambda^2 \mu^4 \ll M_{Pl}^4.$$

If E'_6 is the mirror counterpart of E_6 , then we have Z_2 symmetry, i.e. a discrete group connected with the mirror parity.

In general, the spontaneous breaking of a discrete group leads to phenomenologically unacceptable walls of huge energy per area.

Fig. 7 demonstrates this situation.

Inflation, E_6 unification and the problem of walls

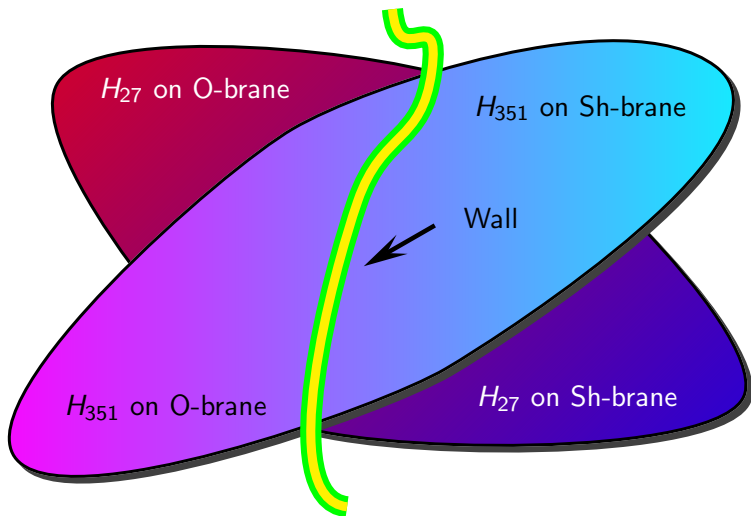


Fig. 7

Inflation, E_6 unification and the problem of walls

Then we have the following properties for the energy densities of radiation, DM, M and wall:

$$\rho_r \propto \frac{1}{a(t)^4}, \quad \rho_{M,DM} \propto \frac{1}{a(t)^3}, \quad \rho_{wall} \propto \frac{1}{a(t)},$$

where $a(t)$ is a scale factor with cosmic time t in the Friedmann-Lemaître-Robertson-Walker (FLRW) metric describing our Universe.

For large Universe we have $\rho_{wall} \gg \rho_{M,DM}, \rho_r$.

In our case of the hidden world, the shadow superpotential is:

$$W' = \lambda' \varphi' (\Phi'^2 - \mu'^2),$$

where $\Phi' = H_{351}$ and $\langle H_{351} \rangle = \mu'$.

Inflation, E_6 unification and the problem of walls

Then the initial energy density in the Sh-world is

$$V' = \lambda'^2 \mu'^4 \ll M_{Pl}^4.$$

To avoid this phenomenologically unacceptable wall dominance we cannot assume symmetry under Z_2 and thus $V = V'$ is not automatic.

Instead, it is necessary to assume the following finetuning:

$$V = V' : \quad \lambda^2 \mu^4 = \lambda'^2 \mu'^4,$$

which helps to obtain the initial conditions for the GUT-scales and GUT-coupling constants:

$$M_{E6} = M'_{E6'},$$

$$g_{E6} = g'_{E6'}.$$

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The cosmological constant problem

The cosmological constant (CC) was first introduced by Einstein in 1917 with aim to admit a static cosmological solution in his new general theory of relativity.

The the bare cosmological constant, λ was accomplished by the addition to the original field equations:

$$G^{\mu\nu} = R^{\mu\nu} - \frac{1}{2}Rg^{\mu\nu} = 8\pi GT^{\mu\nu}$$

of the divergence-free term $-\lambda g_{\mu\nu}$:

$$G^{\mu\nu} = 8\pi GT^{\mu\nu} - \lambda g^{\mu\nu},$$

where $R_{\mu\nu}$ is the Ricci curvature of $g_{\mu\nu}$, and $T_{\mu\nu}$ is the energy-momentum tensor of matter.

The cosmological constant problem

Later it was realized:

See

 [Y. B. Zeldovich](#), JETP Lett. **6** 316 (1967).

 [S. Weinberg](#), Rev. Mod. Phys. **61** 1 (1989).

that quantum fluctuations result in a vacuum energy, ρ_{vac} :

any mode contributes $\frac{1}{2}\hbar\omega$ to the vacuum energy, and the expected value of the energy momentum tensor of matter is:

$$\langle T^{\mu\nu} \rangle = T_m^{\mu\nu} - \rho_{vac} g^{\mu\nu},$$

where $T_m^{\mu\nu}$ vanishes in vacuum.

The cosmological constant problem

The quantum expectation of the energy-momentum tensor, $\langle T^{\mu\nu} \rangle$, acts as a source for the Einstein tensor:

$$G^{\mu\nu} = 8\pi G T_m^{\mu\nu} - \Lambda g^{\mu\nu},$$

where Λ is the effective cosmological constant provided by the contribution of the vacuum energy, ρ_{vac} .

We would expect that the effective vacuum energy:

$$\rho_{vac}^{(eff)} = \frac{\lambda}{8\pi G} + \rho_{vac} = \frac{\Lambda}{8\pi G}$$

to be no smaller than ρ_{vac} .


Even if the “bare” cosmological constant is assumed to vanish ($\lambda = 0$), the effective cosmological constant is not equal to zero.

The cosmological constant problem

Requirement that $\Lambda = 0$ means that there must be an exact cancellation between the bare cosmological constant, λ , and the vacuum energy stress, $8\pi G\rho_{vac}$:

$$\Lambda = 0 \quad \rightarrow \quad \lambda + 8\pi G\rho_{vac} = 0.$$

When the spontaneous symmetry breaking was widely discussed in the Standard Model, Veltman commented that the vacuum energy arising in spontaneous symmetry breaking gives an additional contribution to the CC:

 [M. T. Veltman](#), Phys. Rev. Lett. **34** (1975) 777.

If we assume that the field theory is only valid up to some energy scale M_{cutoff} , then there is a contribution to ρ_{vac} of $O(M_{cutoff}^4)$.

Collider experiments have established that the SM is accurate up to energy scales $M_{cutoff} \gtrsim O(M_{EW})$, where $M_{EW} \approx 246$ GeV is the EW-scale. We would therefore expect ρ_{vac} to be at least $O(M_{EW}^4)$.

The cosmological constant problem

In the absence of any new physics between the electroweak and the Planck scale, $M_{Pl} \approx 1.2 \times 10^{19}$ GeV, where quantum fluctuations in the gravitational field can no longer be safely neglected, we would expect $\rho_{vac} \sim O(M_{Pl}^4)$. If supersymmetry were an unbroken symmetry of Nature, the quantum contributions to the vacuum energy would all exactly cancel leaving $\rho_{vac} = 0$ and $\Lambda = \lambda$. However, our universe is not supersymmetric today, and so SUSY must have been broken at some energy scale M_{SUSY} , where $1 \text{ TeV} \lesssim M_{SUSY} \lesssim M_{Pl}$. It is necessary to comment that the SUSY breaking is necessary in our superstring and thereby SUSY-based model. We would expect $\rho_{vac} \sim O(M_{SUSY}^4)$. Our model of quantum cosmology also had to take into account extra dimensions and branes, spontaneous breaking of compactification.

The cosmological constant problem

Previously in Refs.



C. D. Froggatt, L. V. Laperashvili, R. B. Nevzorov and H. B. Nielsen, Phys. Atom. Nucl. **67** (2004), 582 [Yad. Fiz. **67** (2004), 601]; arXiv:hep-ph/0310127; Proceedings of 7th Workshop on 'What Comes Beyond the Standard Model', Bled, Slovenia, 19-30 Jul 2004; published in *Bled 2004, What comes beyond the standard models*, pp. 17-27, DMFA-Zaloznistvo, Ljubljana, 2004; hep-ph/0412208, hep-ph/0411273.



C. Froggatt, R. Nevzorov and H. B. Nielsen, Nucl. Phys. B **743** (2006) 133, hep-ph/0511259; J. Phys. Conf. Ser. **110** (2008) 072012; arXiv:0708.2907 [hep-ph].

The cosmological constant problem

It was shown that SUGRA models which ensure the vanishing of the vacuum energy density near the physical vacuum lead to a natural realization of **the Multiple Point Model (MPP)**:



D. L. Bennett and H. B. Nielsen,
Int. J. Mod. Phys. A **9** (1994), 5155; *ibid.*, A **14** (1999) 3313;



C. D. Froggatt and H. B. Nielsen,
Origin of Symmetries (World Scientific, Singapore, 1991);



C. D. Froggatt and H. B. Nielsen,
Phys. Lett. B **368** (1996) 96.

MPP describes the degenerate vacua with $\Lambda = 0$.

The cosmological constant problem

The expansion rate of our Universe is sensitive to $\rho_{vac}^{(eff)}$, or equivalently Λ .

The result of astrophysical measurements is given by:

$$(\rho_{vac}^{(eff)})^{1/4} \simeq 2.3 \times 10^{-3} \text{eV}$$

This implies that $\rho_{vac}^{(eff)}$ is some $10^{60} - 10^{120}$ times smaller than the expected contribution from quantum fluctuations, and gives rise to the cosmological constant problem:


“Why is the measured effective vacuum energy or cosmological constant so much smaller than the expected contributions to it from quantum fluctuations?”

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A proposal for solving the CC problem

Here we follow the ideas which gives a possible way to solve the CC problem:

 [D.J. Shaw, J.D. Barrow,](#)
A Testable Solution of the CC and Coincidence Problems,
arXiv:1010.4262[gr-qc].

In quantum mechanics we consider the probability amplitudes: The initial state $|I\rangle$ transforming to a final state $|F\rangle$. In this spirit, using the Euclidian action S_E , only with the Ricci scalar R and CC Λ , E. Baum and S. Hawking have calculated the path integral in the Euclidian space-time:

 [E. Baum,](#) Phys. Lett. B **133** (1983) 185,

 [S. Hawking,](#) Phys. Lett. B **134** (1984) 403.

which gives the following expression:

$$e^{-S_E} = e^{3\pi M_{Pl}/\Lambda}.$$

So, $\Lambda = 0$ dominates the action integral, which is interpreted as the probability for $\Lambda = 0$ is close to 1.

A proposal for solving the CC problem

The essence of the new approach is that the bare cosmological constant λ is promoted from a parameter to a field.

The minimization of the action with respect to λ then yields an additional field equation, which determines the value of the effective CC, Λ . In the classical history it dominates the partition function of the Universe, Z .

If we take the total action of the Universe:

$$S_{tot}(g_{\mu\nu}, \Psi^a, \Lambda; \mathcal{M}),$$

defined on a manifold \mathcal{M} , and with effective cosmological constant Λ , Ψ^a are the matter fields and $g_{\mu\nu}$ is the metric field.

A proposal for solving the CC problem

Then we define $S_{class}(\Lambda; \mathcal{M})$ to be the value of $S_{tot}(g_{\mu\nu}, \Psi^a, \Lambda; \mathcal{M})$ evaluated with $g_{\mu\nu}$ and Ψ^a obeying their classical field equations for fixed boundary initial conditions, and obtain the field equation for the effective $CC = \Lambda$, given by

$$\frac{dS_{class}(\Lambda; \mathcal{M})}{d\Lambda} = 0.$$

If $\Lambda \approx 0$ dominates the action integral, then we have an approximate cancellation between the bare cosmological constant and the vacuum energy stress:

$$\Lambda \approx 0 \quad \rightarrow \quad \lambda \approx -8\pi G \rho_{vac}.$$

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Dark energy: Quintessence model of cosmology

Quintessence is described by a complex scalar field φ minimally coupled to gravity.

In our theory φ is a singlet of E_6 .

The dynamics of two worlds, ordinary and hidden, is governed by the following action:

$$S = \int d^4x \sqrt{-g} \left[\frac{1}{2\kappa^2} R + \lambda + (\nabla\varphi)^2 - V(\varphi) + L + L' + L_{mix} \right],$$

where

$$(\nabla\varphi)^2 = g^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi,$$

and $V(\varphi)$ is the potential of the field φ ,

$\kappa^2 = 8\pi G = M_{Pl}^{-2}$, M_{Pl} is the reduced Planck mass,

R is the space-time curvature, λ is a 'bare' cosmological constant,

$L(L')$ is the Lagrangian of the O-(Sh-) sector,

Dark energy: Quintessence model of cosmology

and L_{mix} is the Lagrangian of photon-photon', neutrino-neutrino', etc. mixing:



Z. Berezhiani,

Through the looking-glass: Alice's adventures in mirror world, in: Ian Kogan Memorial Collection "From Fields to Strings: Circumnavigating Theoretical Physics", Eds. M. Shifman et al., World Scientific, Singapore, Vol. 3, pp. 2147-2195, 2005; AIP Conf. Proc. **878** (2006) 195; Eur. Phys. J. ST **163** (2008) 271.

When both E_6 and E'_6 symmetry groups are broken, then down to G_{SM} and $G'_{SM} \times SU(2)'_\theta$ subgroups, respectively, we have:

$$L = L_{gauge} + L_{Higgs} + L_{Yuk},$$

$$L' = L'_\theta + L'_{gauge} + L'_{Higgs} + L'_{Yuk},$$

$$L_{tot} = L + L' + L_{mix}.$$

Dark energy: Quintessence model of cosmology

The two sectors mean that at least below the scales $M_R = M'_R$ the degrees of freedoms (fields) can be classified into fields from section O and fields from section H (hidden).

Since this moment and further: $H(hidden) \equiv Sh(shadow)$.

We could thus consider the energy density due to zero point fluctuations in the H-fields as contributing to $\rho_{vac}^{(H)}$ while the O-fields contribute to $\rho_{vac}^{(O)}$.

Here we see that

$$\rho_{vac}^{(O)} = \rho_{vac}^{(SM)},$$

and

$$\rho_{vac}^{(H)} = \rho_{vac}^{(SM')} + \rho_{vac}^{(\theta)}.$$

$$\rho_{vac} = \rho_{vac}^{(O)} + \rho_{vac}^{(H)} + \rho_{vac}^{(mix)}.$$

We can neglect $\rho_{vac}^{(mix)}$.

Dark energy: Quintessence model of cosmology

Then assuming that the 'bare' cosmological constant λ compensates the contribution of the SM and SM', e.g.

$$\rho_{vac}^{(SM-SM')} = \rho_{vac}^{(SM)} + \rho_{vac}^{(SM')}$$

giving

$$\lambda + 8\pi G \rho_{vac}^{(SM-SM')} = 0.$$

Then the effective CC, Λ , is not zero:

$$\Lambda = 8\pi G \rho_{vac}^{(\theta)},$$

and the effective vacuum energy density is equal to DE density:

$$\rho_{DE} = \rho_{vac}^{(eff)} = \rho_{vac}^{(\theta)}.$$

This speculative consideration explains a tiny value of the DE density calculated into the next Section.

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Dark energy: Inflaton, axion and DE density

We assume that there exists an axial $U(1)_A$ global symmetry in our theory, which is spontaneously broken at the scale f by a singlet complex scalar field φ :

$$\varphi = (f + \sigma) \exp(ia_{ax}/f).$$

We assume that a VEV

$$\langle \varphi \rangle = f$$

is of the order of the E_6 unification scale: $f \sim 10^{18}$ GeV.

The real part σ of the field φ is the inflaton, while the boson a_{ax} (imaginary part of the singlet scalar fields φ) is an axion and could be identified with the massless Nambu-Goldstone (NG) boson if the corresponding $U(1)_A$ symmetry is not explicitly broken by the gauge anomaly.

Dark energy: Inflaton, axion and DE density

However, in the hidden world the explicit breaking of the global $U(1)_A$ by $SU(2)'_\theta$ instantons inverts a_{ax} into a pseudo Nambu-Goldstone (PNG) boson a_θ . Therefore, in the Sh-world we have:

$$\varphi' = (f + \sigma') \exp(ia_\theta/f).$$

The flat FLRW spacetime gives the following field equation for axion a_θ :

$$\frac{d^2 a_\theta}{dt^2} + 3H \frac{da_\theta}{dt} + V'(a_\theta) = 0.$$

where H is the Hubble parameter.

Dark energy: Inflaton, axion and DE density

The singlet complex scalar field φ reproduces a Peccei-Quinn (PQ) model. Near the vacuum, a PNG mode a_θ emerges the following PQ axion potential:

$$V_{PQ}(a_\theta) \approx (\Lambda'_\theta)^4 (1 - \cos(a_\theta/f)).$$

This axion potential exhibits minima at

$$(V_{PQ})|_{min} = 0,$$

where:

$$\cos(a_\theta/f) = 1, \quad \text{i.e.} \quad (a_\theta)_{min} = 2\pi n f, \quad n = 0, 1, \dots$$

Dark energy: Inflaton, axion and DE density

For small fields a_θ we expand the effective PQ potential near the minimum:

$$V_{PQ}(a_\theta) \approx \frac{(\Lambda'_\theta)^4}{2f^2}(a_\theta)^2 + \dots = \frac{1}{2}m^2(a_\theta)^2 + \dots,$$

and hence the PNG axion mass squared is given by:

$$m^2 \sim (\Lambda'_\theta)^4/f^2.$$

Solving equation for a_θ we can use the axion potential:

$$V(a_\theta) = V_{PQ}(a_\theta),$$

which gives:

$$V'(a_\theta) = \frac{(\Lambda'_\theta)^4}{f} \sin(a_\theta/f).$$

If now $\sin(a_\theta/f) = 0$,

then $\dot{a}_\theta = 0$,

and $V_{PQ}(a_\theta) = 0$,

because $\cos(a_\theta/f) = 1$, according to minima.

Dark energy: Inflaton, axion and DE density

The minimum of the total θ -potential is:

$$V_{\theta}|_{min} = V_{PQ}(a_{\theta})|_{min} + V_{\theta-condensate}.$$

The first term is zero and we obtain:

$$V_{\theta-condensate} = (\Lambda'_{\theta})^4.$$

In this case when $a_{\theta} = \text{const}$ and $\dot{a}_{\theta} = 0$, the contribution of axions to the energy density of the Sh-sector is equal to zero.

Finally, we obtain:

$$\rho_{vac}^{(eff)} = \rho_{vac}^{(\theta)} = |\dot{a}_{\theta}|^2 + V_{\theta}|_{min} = (\Lambda'_{\theta})^4.$$

Dark energy: Inflaton, axion and DE density

The DE density is equal to the value:

$$\rho_{DE} = \rho_{vac}^{(eff)} = (\Lambda'_\theta)^4.$$

Taking into account the results of recent astrophysical observations, we obtain the estimate of the $SU(2)'_\theta$ group's gauge scale:

$$\Lambda'_\theta \simeq 2.3 \times 10^{-3} \text{ eV}.$$

If $\Lambda'_\theta \sim 10^{-3} \text{ eV}$ and $f \sim 10^{18} \text{ GeV}$, we can estimate the θ -axion mass:

$$m \sim \Lambda'^2_\theta / f \sim 10^{-42} \text{ GeV}.$$

It is extremely small.

We have seen that these light axions do not give the contribution to ρ_{DE} . It is given only by the condensate of θ -fields.

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Reheating and radiation

The two sectors, ordinary and hidden, have different cosmological evolutions. In particular, they never had to be in equilibrium with each other: the Big Bang Nucleosynthesis (BBN) constraints require that Sh-sector must have smaller temperature than O-sector: $T' < T$.

See



Z. Berezhiani, L. Kaufmann, P. Panci, N. Rossi, A. Rubbia and A. Sakharov,

Strongly interacting mirror dark matter, CERN-PH-TH-2008-108, May 2008.

Since this moment and further: Ref. BKPRRS.

During reheating the exponential expansion, which was developed by inflation, ceases and the potential energy of the inflaton field decays into a hot relativistic plasma of particles. At this point, the Universe is dominated by radiation, and then quarks and leptons are formed.

Reheating and radiation

All the difference between the O- and Sh- worlds can be described in terms of two macroscopic (free) parameters of the model:

$$x \equiv \frac{T'}{T}, \quad \beta \equiv \frac{\Omega'_B}{\Omega_B},$$

where $T(T')$ is O-(Sh-) photon temperature in the present Universe, and $\Omega_B(\Omega'_B)$ is O-(Sh-)baryon fraction.

The modern observational data indicate that the Universe is almost flat, in a perfect accordance with the inflationary paradigm.

The relativistic fraction is represented by photons and neutrinos.

Reheating and radiation

The contribution of the Sh-degrees of freedom to the observable Hubble expansion rate, which are equivalent to an effective number of extra neutrinos

$$\Delta N_\nu = 6.14 \cdot x^4,$$

is small enough:

$$\Delta N_\nu = 0.05 \quad \text{for} \quad x = 0.3.$$

In our model:

$$\omega_r = \Omega_r h^2 = 4.2 \cdot 10^{-5} (1 + x^4), \quad h = \frac{H}{H_0},$$

where the contribution of Sh-species is negligible due to the BBN constraint: $x^4 \ll 1$.

Recent cosmological observations show that for redshifts

$$(1 + z) \gg 1$$

we have:

$$H(z) = H_0[\Omega_r(1 + z)^4 + \Omega_m(1 + z)^3].$$

Therefore, the radiation is dominant at the early epochs of the Universe, but it is negligible at present epoch:

$$\Omega_r^{(0)} \ll 1.$$

Reheating and radiation

Any inflationary model have to describe how the SM-particles were generated at the end of inflation. The inflaton, which is a singlet of E_6 , can decay, and the subsequent thermalization of the decay products can generate the SM-particles. The inflaton σ produces gauge bosons: photons, gluons, W^\pm , Z , and matter fields: quarks, leptons and the Higgs bosons, while the inflaton field σ' produces Sh-world particles: shadow photons and gluons, thettons, W' , Z' , theta-quarks q_θ , theta-leptons l_θ , shadow quarks q' and leptons l' , scalar bosons ϕ_θ and shadow Higgs fields ϕ' . In shadow world we end up with a thermal bath of SM' and θ particles. However, we assume that the density of theta-particles is not too essential in cosmological evolution due to small θ coupling constants.

Reheating and radiation

According to investigations of Ref. BKPRRS

at the end of inflation the O- and Sh-sectors are reheated in a non-symmetric way: $T_R > T'_R$.

After reheating (at $T < T_R$) the exchange processes between O- and H-worlds are too slow, by reason of very weak interaction between two sectors. As a result, it is impossible to establish equilibrium between them. So that both worlds evolve adiabatically and the temperature asymmetry ($T'/T < 1$) is approximately constant in all epochs from the end of inflation until the present epoch.

Therefore, the cosmology of the early Sh-world is very different from the ordinary one when we consider such crucial epochs as baryogenesis and nucleosynthesis.

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Big Bang Nucleosynthesis

At the end of cosmic inflation the Universe was filled with a quark-gluon plasma. This plasma cools until **the hadron epoch** when hadrons (including baryons) can form.

Then neutrinos decouple and begin travelling freely through space. This cosmic neutrino background is analogous to the CMB which was emitted much later.

After hadron epoch the majority of hadrons and anti-hadrons annihilate each other, leaving leptons and anti-leptons dominating the mass of the Universe.

Here we reach **the lepton epoch**.

Then the temperature of the Universe continues to fall and falls until the stop of the lepton/anti-lepton pairs creation. Also the most leptons/anti-leptons are eliminated by annihilation processes.

Big Bang Nucleosynthesis

At the end of the lepton epoch the Universe undergoes **the photon epoch** when the energy of the Universe is dominated by photons, which still essentially interact with charged protons, electrons and eventually nuclei.

The temperature of the Universe again continues to fall. It falls to the point when atomic nuclei begin to form. Protons and neutrons combine into atomic nuclei by nuclear fusion process. However, this nucleosynthesis stops at the end of the nuclear fusion. At this time, the densities of non-relativistic matter (atomic nuclei) and relativistic radiation (photons) are equal.

The BBN epoch in the Sh-world proceeds differently from ordinary one and predicts different abundances of primordial elements.

The difference of the temperatures ($T' < T$) gives that the number density of H-photons is much smaller than for O-photons:

$$\frac{n'_\gamma}{n_\gamma} = x^3 \ll 1.$$

Big Bang Nucleosynthesis

The primordial abundances of light elements depend on the baryon to photon number density ratio: $\eta = n_B/n_\gamma$. The result of WMAP gives: $\eta \simeq 6 \cdot 10^{-10}$, in accordance with the observational data.

The universe expansion rate at the ordinary BBN epoch (with $T \sim 1$ MeV) is determined by the O-matter density itself. As far as $T' \ll T$, for the ordinary observer it is difficult to detect the contribution of Sh-sector, which is equivalent to $\Delta N_\nu \approx 6.14x^4$ and negligible for $x \ll 1$.

As for the BBN epoch in the shadow world, for the Sh-observer the contribution of O-sector is equivalent to $\Delta N'_\nu \approx 6.14x^{-4}$, which is dramatically large. Therefore, the observer in Sh-world, which measures the abundances of shadow light elements, should immediately detect the discrepancy between the universe expansion rate and Sh-matter density at the shadow BBN epoch (with $T' \sim 1$ MeV): the O-matter density is invisible for the Sh-observer.

Big Bang Nucleosynthesis. Recombination

Then the most of electrons and protons recombine into neutral hydrogen and free electron density strongly diminishes. During the recombination the photon scattering rate drops below the Hubble expansion rate.

Thus, at the end of recombination, most of the atoms in the Universe is neutral, photons travel freely and the Universe becomes transparent. The observable CMB is a picture of the Universe at the end of this epoch.

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Baryon density and dark matter

Shadow baryons (and shadow helium), which are invisible by ordinary photons, are the best candidates for dark matter (DM).

Here we give an approximate estimate of baryon masses in the O- and Sh-worlds.

The most part of mass of nucleons (proton and neutron) is provided with dynamical (constituent) quark masses m_q forming the nucleon. The dynamical quark mass is

$$m_q \simeq m_0 + \Lambda_{QCD},$$

where $m_0 \sim 10$ MeV is a current mass of light quarks u , d , and

$$\Lambda_{QCD} \simeq 300 \text{ MeV}.$$

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Baryon density and dark matter

Then the nucleon mass M_B can be estimated as

$$M_B \simeq 3m_q \simeq 1 \text{ GeV}.$$

As to shadow current quark mass m'_0 , we have

$$m'_0 \simeq \zeta m_0 \sim 1 \text{ GeV}$$

for $\zeta \sim 100$.

This estimate gives the shadow baryon mass M'_B equal to

$$M'_B \simeq 3(m'_0 + \Lambda'_{QCD}).$$

Baryon density and dark matter

Taking into account Ref.



Z. Berezhiani,

Through the looking-glass: Alice's adventures in mirror world, in: Ian Kogan Memorial Collection "From Fields to Strings: Circumnavigating Theoretical Physics", Eds. M. Shifman et al., World Scientific, Singapore, Vol. 3, pp. 2147-2195, 2005; AIP Conf. Proc. **878** (2006) 195; Eur. Phys. J. ST **163** (2008) 271

we obtain

$$\Lambda'_{QCD} \simeq 450 \text{ MeV},$$

and:

$$M'_B \simeq 3(1 + 0.45) \text{ GeV} \simeq 4.35 \text{ GeV}.$$

Here we want to comment that in our model baryons of shadow world are formed not only by quark system qqq , but also by $q_{\theta,\vartheta} q_{\theta}^{\vartheta} q$, where $\vartheta = 1, 2$ is the index of $SU(2)'_{\theta}$ -group. The last system gives the quark-diquark structure of shadow baryons. However, they do not give essential contributions to baryon density, by reason of small theta-charges.

Since Sh-sector is cooler than the ordinary one, then we have $n'_B \gtrsim n_B$ by estimate of Ref. BKPRRS

And:

$$\rho'_B = n'_B M'_B > \rho_B = n_B M_B.$$

Now we can explain the value ρ_{DM} , especially if we take into account the shadow helium mass fraction.

Baryon density and dark matter

Finally, we predict that the energy density of Sh-sector is:

$$\rho' = \rho_{DE} + \rho_{DM} = \rho_{DE} + \rho'_B + \rho_{CDM},$$

where $\rho'_B = n'_B M'_B \approx 0.17\rho_c$ and $\rho_{CDM} \approx 0.04\rho_c$ presumably contains shadow helium.

The energy density of the O-world is;

$$\rho_M = \rho_B + \rho_{nuclear},$$

where $\rho_B = n_B M_B \approx 0.04\rho_c$ and the contribution of ordinary helium and other atoms is much smaller.

Then it is possible to explain the following observable result:

$$\frac{\Omega_{DM}}{\Omega_M} \simeq \frac{\rho_{DM}}{\rho_M} \simeq \frac{\rho'_B + \rho_{CDM}}{\rho_B + \rho_{nuclear}} \simeq \frac{0.17 + 0.04}{0.04} \simeq 5.$$

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Baryogenesis

It is necessary to devote a separate talk for **Baryogenesis**

In our cosmological model with superstring-inspired E_6 unification, the $B - L$ asymmetry is produced by the conversion of ordinary leptons into particles of the hidden sector. After the non-symmetric reheating with $T_R > T'_R$, it is impossible to establish equilibrium between the O- and Sh-sectors, and baryon asymmetry may be generated even by scattering of massless particles. In our model with E_6 -unification existing at the early stage of the Universe, after the breaking of $E_6(E'_6)$, heavy Majorana neutrinos N_a become singlets of the subgroups $SU(3)_C \times SU(2)_L \times U(1)_X \times U(1)_Z$ and $SU(3)'_C \times SU(2)'_L \times U(1)'_X \times U(1)'_Z$, and can play the role of messengers between O- and Sh-worlds. $B - L$ quantum number is generated in the decays of heavy Majorana neutrinos, N , into leptons l (or anti-leptons \bar{l}) and the Higgs bosons ϕ : $N \rightarrow l\phi, \bar{l}\bar{\phi}$.

Baryogenesis

The three necessary Sakharov conditions, given by Ref.



A.D. Sakharov, Pisma Zh. Eksp. Teor. Fiz. **5** (1967) 32.

are realized in our model of baryogenesis:

- 1 $B - L$ and L are violated by the heavy neutrino Majorana masses.
- 2 The out-of-equilibrium condition is satisfied due to the delayed decay(s) of the Majorana neutrinos, when the decay rate $\Gamma(N)$ is smaller than the Hubble rate H : $\Gamma(N) < H$, i.e. the life-time is larger than the age of the Universe at the time when N_a becomes non-relativistic.
- 3 CP-violation (C is trivially violated due to the chiral nature of the fermion weak eigenstates) originates as a result of the complex $IN\phi$ Yukawa couplings producing asymmetric decay rates:

$$\Gamma(N \rightarrow l\phi) \neq \Gamma(N \rightarrow \bar{l}\bar{\phi}),$$

so that leptons and anti-leptons are produced in different amounts and the $B - L$ asymmetry is generated.

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Conclusions

- In this paper we have developed the hypothesis of parallel existence of the ordinary (O) and hidden (Sh) sectors of the Universe.
- We have constructed a new cosmological model with the superstring-inspired E_6 unification in the 4-dimensional space.
- We have assumed that this unification was broken at the early stage of the Universe into

$$SO(10) \times U(1)_Z$$

– in the O-world,
and

$$SU(6)' \times SU(2)'_\theta$$

– in the Sh-world.

- We have investigated the breaking mechanism of the E_6 unification. In the O-world this breaking is realized with the Higgs field H_{27} belonging to the 27-plet, while in the hidden sector the breakdown of the E'_6 unification has come true due to the Higgs field H_{351} belonging to the 351-plet of the E'_6 . The corresponding VEVs are $v = \langle H_{27} \rangle$ and $V = \langle H_{351} \rangle$.

- From the beginning, we have assumed that E'_6 is the mirror counterpart of the E_6 . Then the discrete symmetry Z_2 (connected with the mirror parity MP) leads to the phenomenologically unacceptable wall. Using the simplest model of inflation with the superpotential $W = \lambda\varphi(\Phi^2 - \mu^2)$, where the field φ is the inflaton and Φ is the Higgs field, (λ is a coupling constant and μ is a dimensional parameter of the order of the GUT scale $\sim 10^{18}$ GeV), we avoid this unacceptable wall dominance assuming the following fine-tuning:

$$V = V',$$

what gives $\lambda^2\mu^4 = \lambda'^2\mu'^4$. Here $V^{(')} = \lambda^{(')2}\mu^{(')4}$ is the energy density of the tree level potential.

Conclusions

- According to our assumptions, there exists the following chains of symmetry groups:

$$\begin{aligned} E_6 &\rightarrow SO(10) \times U(1)_Z \rightarrow SU(4)_C \times SU(2)_L \times SU(2)_R \times U(1)_Z \\ &\rightarrow SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_X \times U(1)_Z \\ &\rightarrow [SU(3)_C \times SU(2)_L \times U(1)_Y]_{SUSY} \rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y \end{aligned}$$

- in the O-world,
and

$$\begin{aligned} E'_6 &\rightarrow SU(6)' \times SU(2)'_\theta \rightarrow SU(4)'_C \times SU(2)'_L \times SU(2)'_\theta \times U(1)'_Z \\ &\rightarrow SU(3)'_C \times SU(2)'_L \times SU(2)'_\theta \times U(1)'_X \times U(1)'_Z \\ &\rightarrow [SU(3)'_C \times SU(2)'_L \times SU(2)'_\theta \times U(1)'_Y]_{SUSY} \\ &\rightarrow SU(3)'_C \times SU(2)'_L \times SU(2)'_\theta \times U(1)'_Y \end{aligned}$$

- in the Sh-world.

Conclusions

- In contrast to the results of Refs. of Berezhiani et al, based on the concept of the parallel existence in Nature of the mirror (M-) and ordinary (O-) worlds described by a minimal symmetry $G_{SM} \times G'_{SM}$, we assume the existence of low-energy symmetry group $G' = SU(3)'_C \times SU(2)'_L \times SU(2)'_\theta \times U(1)'_Y$ in the Sh-world and the SM symmetry group in the O-world. This is a natural consequence of different schemes of the E_6 -breaking in the O- and Sh-worlds. In comparison with G_{SM} , the group G' has an additional non-Abelian $SU(2)'_\theta$ group whose gauge fields are massless vector particles 'thetons'. These 'thetons' have a macroscopic confinement radius $1/\Lambda'_\theta$. The estimate confirms the scale $\Lambda'_\theta \sim 10^{-3}$ eV.
- Assuming the cancellation between the bare cosmological constant, λ , and the vacuum energy stress, $8\pi G\rho_{vac}$, described only by the SM contributions of the O- and Sh-worlds, we explain the small value of ρ_{DE} , i.e. the observable tiny CC, only as a result of the theta-fields condensation: $\rho_{DE} = \rho_{vac}^{(eff)} = (\Lambda'_\theta)^4 \simeq (2.3 \times 10^{-3} \text{ eV})^4$.

Conclusions

- We have discussed how the SM-particles were generated at the end of inflation: the inflaton decays, and the subsequent thermalization of these decay products generates the SM-particles. The inflaton σ produces gauge bosons: photons, gluons, W^\pm , Z , and matter fields: quarks, leptons and the Higgs bosons, while the inflaton σ' produces hidden particles: shadow photons, gluons and 'thetons', W' , Z' , theta-quarks q_θ , theta-leptons l_θ , shadow quarks q' and shadow leptons l' , scalar bosons ϕ_θ and shadow Higgs fields ϕ' .
- The O- and Sh-sectors have different cosmological evolutions: they never had to be in equilibrium with each other. The Big Bang Nucleosynthesis (BBN) constraints require that Sh-sector must have smaller temperature than O-sector: $T' < T$. The difference between the O- and Sh-worlds is described in terms of two macroscopic parameters: $x \equiv T'/T$, $\beta \equiv \Omega'_B/\Omega_B$, where $T(T')$ is O-(Sh-) photon temperature of the Universe at present, and $\Omega_B(\Omega'_B)$ is O-(Sh-)baryons fraction.

Conclusions

- We have considered the reheating and radiation and Big Bang Nucleosynthesis. During reheating the exponential expansion, developed by inflation, ceases and the potential energy of the inflaton field decays into a hot relativistic plasma of particles. The relativistic fraction is represented by photons and neutrinos. The radiation is dominant at the early epochs of the Universe, but it is negligible at present epoch: $\Omega_r^{(0)} \ll 1$.
- The contribution of the Sh-degrees of freedom to the observable Hubble expansion rate, which are equivalent to an effective number of extra neutrinos $\Delta N_\nu = 6.14 \cdot x^4$, is small enough. In our model: $\omega_r = \Omega_r h^2 = 4.2 \cdot 10^{-5} (1 + x^4)$ ($h = H/H_0$), where the contribution of Sh-species is negligible due to the BBN constraint: $x^4 \ll 1$.

Conclusions

- At the end of inflation the O- and H-sectors are reheated in a non-symmetric way: $T_R > T'_R$. After reheating, at $T < T_R$, the exchange processes between O- and Sh-worlds are too slow (by reason of very weak interaction between two sectors), and it is difficult to establish equilibrium between them. As a result, the temperature asymmetry ($T'/T < 1$) is approximately constant from the end of inflation until the present epoch.
- We have seen that the cosmological evolutions of the early O- and Sh-worlds are very different, in particular, when we consider such crucial epochs as baryogenesis and nucleosynthesis. The BBN epoch proceeds differently in the O- and Sh-worlds and predicts different abundances of primordial elements. For example, due to the condition $T' < T$ the density of Sh-photons number is much smaller than for O-photons: $n'_\gamma/n_\gamma = x^3 \ll 1$.

Conclusions

- The structure formation in the Universe is connected with the plasma recombination and matter-radiation decoupling (MRD) epochs. Also the matter-radiation equality (MRE) is important, which is given by the relation

$$1 + z_{eq} = \Omega_m / \Omega_r \simeq 2.4 \cdot 10^4 \cdot \Omega_m h^2 / (1 + x^4).$$

During the MRD epoch the most of electrons and protons recombine into neutral hydrogen and the free electron density essentially diminishes. The MRD temperature is $T_{dec} \simeq 0.26$ eV what corresponds to the redshift $1 + z_{dec} = T_{dec} / T_{today} \simeq 1100$. In the Sh-world we have the MRD temperature $T'_{dec} \simeq T_{dec}$ and $1 + z'_{dec} \simeq x^{-1}(1 + z_{dec}) \simeq 1100/x$, what means that in the Sh-world MRD occurs earlier than in the O-world.

Conclusions

- During the recombination epoch the photon scattering rate drops below the Hubble expansion rate. The Sh-photon decoupling epoch coincides with the MRE epoch. At the end of recombination, the atoms in the Universe are neutral, photons travel freely and the Universe becomes transparent. The observation of CMB gives a picture of the Universe at the end of this epoch.
- We have estimated ρ_M and ρ_{DM} in the framework of our cosmological model. We assume that shadow baryons and shadow helium, invisible for ordinary photons, give the main contribution to dark matter (DM). We explain the observable result: $\Omega_{DM}/\Omega_M \simeq \rho_{DM}/\rho_M \simeq 5$.

Conclusions

- In our cosmological model with E_6 unification, the $B - L$ asymmetry is produced by the conversion of ordinary leptons into particles of the hidden sector. After the non-symmetric reheating with $T_R > T'_R$, it is impossible to establish equilibrium between the O- and Sh- sectors, and baryon asymmetry may be generated even by scattering of massless particles.

After the breaking of $E_6(E'_6)$, heavy Majorana neutrinos N_a become singlets of the subgroups $SU(3)_C \times SU(2)_L \times U(1)_X \times U(1)_Z$ and $SU(3)'_C \times SU(2)'_L \times U(1)'_X \times U(1)'_Z$, and can play the role of messengers between O- and Sh-worlds. $B - L$ quantum number is generated in the decays of heavy Majorana neutrinos into leptons or anti-leptons and the Higgs bosons.

The three necessary Sakharov's conditions are realized in our model of baryogenesis.